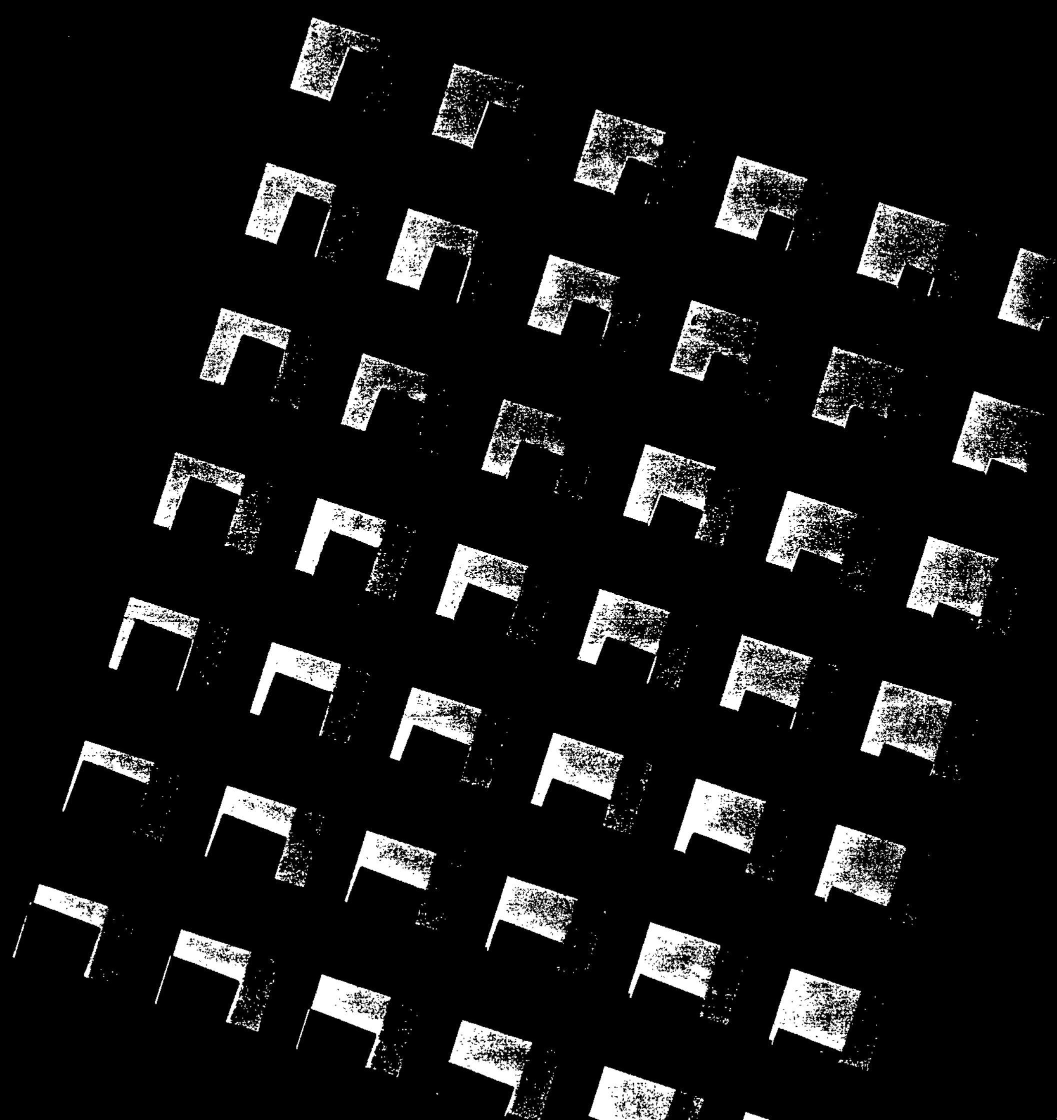
TNO-report
TM-97-B010

title
Interference between 6 degrees of freedom in a 3D hand controller

TNO Human Factors
Research Institute



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Interference between 6 degrees of freedom in a 3D hand controller

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Management uittreksel TNO Technische Menskunde, Soesterberg

titel:	Interferentie tussen vrijheidsgraden bij een 3D stuurmiddel
auteurs:	Dr. J.E. Korteling, drs. A. Oving, drs. M.L. van Emmerik en drs. J.B.F. van Erp
datum:	4 juli 1997
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Een hand controller met zes vrijheidsgraden (Degree-of-Freedom, DOF) kan worden gebruikt als bedieningsmiddel voor continue besturing van meer-assige systemen. Dergelijke systemen zijn vaak te vinden in gebieden als remote manipulation of teleoperation. Met een 6 DOF hand controller is een bestuurder in staat om met één hand meer dan één as of vrijheidsgraad tegelijkertijd te besturen. Een probleem met het uitvoeren van meer-assige taken met dergelijke geïntegreerde besturingsmiddelen is echter de mogelijkheid van interferentie tussen vrijheidsgraden, waarbij het besturen van een bepaalde vrijheidsgraad hinder ondervindt van het (tegelijkertijd) kunnen besturen van een andere vrijheidsgraad. Deze interferentie kan het gevolg zijn van beperkingen van het motorisch systeem en het informatieverwerkingssysteem van de menselijke bestuurder. Hierdoor kan de prestatie op de taak die moet worden uitgevoerd, afnemen. Daarbij is het mogelijk dat deze eventuele interferentie een systematisch karakter heeft, waarbij de input op een bepaalde vrijheidsgraad resulteert in (ongewenste) samenhangende input op een andere vrijheidsgraad. In dit geval is er sprake van cross talk of overspraak. Daarnaast kan het aantal vrijheidsgraden dat tegelijkertijd kan worden bestuurd van invloed zijn op de taakuitvoering, doordat bij een toenemend aantal bestuurbare vrijheidsgraden de beperkingen van de bestuurder waarschijnlijk een grotere rol zullen gaan spelen. Het onderhavige exploratieve experiment had als doel het optreden van bovenstaande mogelijke verschijnselen in kaart te brengen.

In het experiment werd een compensatoire volgtaak uitgevoerd, waarbij steeds één vrijheidsgraad van een cursor in een perspectivisch display (extern) werd verstoord. De proefpersonen dienden deze verstoring te compenseren door input te leveren op de relevante vrijheidsgraad middels een 6 DOF hand controller. De compensatoire taak werd voor elke vrijheidsgraad van de 6 DOF hand controller uitgevoerd, te weten: X, Y, Z, Roll, Pitch en Yaw (drie translaties en drie rotaties). Daarnaast werd de volgtaak verricht met respectievelijk 0, 1 en 5 volgtaak-irrelevante vrijheidsgraden naast de ene volgtaak-relevante vrijheidsgraad. Hierbij kregen de proefpersonen visuele feedback over de beweging ten gevolge van hun (onbedoelde) input op deze irrelevante vrijheidsgraden. De proefpersonen konden dus respectievelijk 1, 2 en 6 vrijheidsgraden tegelijkertijd (zichtbaar) besturen. De input op de irrelevante vrijheidsgraden moest hierbij tot een minimum worden beperkt. Eventuele afwijkingen tussen de target en cursor voor deze irrelevante vrijheidsgraden waren dus geheel het gevolg van incorrecte en onbedoelde stuurbewegingen. Dit in tegenstelling tot afwijkingen voor de relevante vrijheidsgraden, die veroorzaakt worden door een externe verstoring én eventuele incorrecte stuurinput.

De prestatie op de relevante vrijheidsgraad en de mate waarin de proefpersonen onbedoelde input leverden op de irrelevante vrijheidsgraden (beiden uitgedrukt in RMS error) kunnen worden beschouwd als een indicatie van de mate van interferentie tussen vrijheidsgraden. Hierbij werden de scores voor zowel de relevante vrijheidsgraad als de irrelevante vrijheidsgraden in de verschillende condities gedeeld door de gemiddelde RMS error over de twee blokken in de 1-vrijheidsgraad conditie. De scores werden dus uitgedrukt als een percentage van de gemiddelde prestatie in de conditie waarbij alleen de relevante vrijheidsgraad kon worden bestuurd. Op deze wijze kon inzicht worden verkregen in de prestatie af- of toename per vrijheidsgraad onder invloed van het aantal zichtbare vrijheidsgraden dat tegelijkertijd kon worden bestuurd. Door het bepalen van de correlatie tussen de stuurinput van de proefpersonen op een relevante vrijheidsgraad en de stuurinput op een irrelevante vrijheidsgraad (i.e. een combinatie van twee vrijheidsgraden) werd inzicht verkregen in de systematische interferentie (of overspraak) tussen twee vrijheidsgraden.

De resultaten van het experiment lieten zien dat er in de 1-vrijheidsgraad conditie het minst werd gepresteerd met Z bij de translatoire vrijheidsgraden en met Pitch bij de rotationele vrijheidsgraden. Dit kan te maken hebben met de weergave van de z-as (i.e. gebruikte diepte cues en mate van compressie) in het gebruikte perspectivische display. Met betrekking tot interferentie tussen vrijheidsgraden bleek dat de prestatie voor zowel een relevante vrijheidsgraad als voor een irrelevante vrijheidsgraad afnam wanneer er over meerdere vrijheidsgraden tegelijkertijd visuele feedback werd gegeven. Deze beperkingen hangen waarschijnlijk samen met capaciteitsbeperkingen in de menselijke informatieverwerking. Ten opzichte van de andere DOFs bleek deze beperking voor Z relatief substantieel, terwijl dit capaciteitseffect voor X juist relatief klein was (zowel in de relevante als in de irrelevante situatie). Verondersteld wordt dat er voor Z relatief meer aandacht en voor X relatief minder aandacht nodig is, vanwege de verschillen in de effectiviteit waarmee informatie over deze twee vrijheidsgraden werd gepresenteerd. De mate van interferentie bleek af te nemen naarmate de proefpersonen meer ervaring kregen. Dit leereffect was voor elke conditie en voor elke vrijheidsgraad even groot.

Er bleek altijd sprake van systematische samenhang tussen de input op een relevante vrijheidsgraad en de input op een irrelevante vrijheidsgraad. Voor bijna de helft van de onderzochte combinaties van twee vrijheidsgraden bleek het wel of niet geven van visuele feedback de hoogte van de correlaties niet te beïnvloeden. Toename in het aantal vrijheidsgraden waarover deze feedback werd gegeven had voor geen van de onderzochte combinaties effect op de hoogte van de overspraak. De geconstateerde overspraak lijkt dan ook hoofdzakelijk een gevolg van beperkingen van het motorisch systeem van de menselijke bestuurder. Door het verbeteren van de haptisch informatie die de 6 DOF hand controller levert, kunnen de verschillende vrijheidsgraden waarschijnlijk beter van elkaar worden onderscheiden, waardoor de overspraak kan afnemen.

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Interference between 6 degrees of freedom in a 3D hand controller

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15. **ABSTRACT (MAXIMUM 200 WORDS (1044 BYTES))**

A six degree of freedom (DOF) hand controller is a device that can be used for the simultaneous control of multiple axes. These kinds of control tasks are common in areas such as teleoperation. Multi-axis control may be problematic as a consequence of interference i.e., the control of a certain DOF affected the simultaneous control of another. Irrespective whether the cause of this interference lies in the operator's motor system or in his information processing system, it can be detrimental to task performance. When input on one DOF always results in undesired input on another DOF, the nature of this interference is systematic (cross-talk). The magnitude of the interference is probably affected by the number of DOFs that has to be controlled simultaneously. This was investigated in an experiment in which a compensatory tracking task was performed. In this task one DOF of a cursor in a perspective display was disturbed (externally). Subjects had to compensate this disturbance using a 6-DOF hand controller. At the same time they had to minimize input on the other (irrelevant to tracking) DOFs. It was investigated whether there were differences between tracking performance between each separate degree of freedom (X, Y, Z, Roll, Pitch, or Yaw). Furthermore, the effect of additional (irrelevant) DOFs that had to be controlled simultaneously (0, 1, or 5), was examined. With regard to the irrelevant degrees of freedom, the steering error thus was completely caused by incorrect, accidental, steering inputs. Error on the relevant DOF was a sum of this incorrect steering input and the disturbance signal.

Both these errors (expressed in RMS scores) can be used to indicate the extent to which degrees of freedom interfered with each other. In this experiment a relative RMS score was calculated by dividing the RMS score with the mean RMS error score from the 1-DOF condition (no irrelevant DOFs) that was used as a baseline condition. This way, it was possible to gain insight in the performance increment or decrement as a function of the number of DOFs that had to be controlled. Through determination of the correlations between each combination of two degrees of freedom the extent to which systematic interference occurred was investigated.

The experimental results show that in the 1-DOF condition tracking error was largest on Z with regard to translations and on Pitch with regard to rotations. This can be related to the effectivity of the presentation of the z-axis (i.e., used depth cues and compression) in the used perspective display. Furthermore, performance on relevant as well as irrelevant DOFs decreased when the number of visible degrees of freedom that had to be controlled increased. These limitation are attributed to the limited information processing capacity of the human operator. In relation to the other DOFs, this performance decrement for Z was substantially larger whereas it was smaller for X Again this may be related to the effectivity of presentation of the different axes on the display. A clear training effect diminished the effect of interference in the second block of trials. For each DOF in each condition this effect was of the same magnitude.

Input on a relevant DOF and input on an irrelevant DOF were always significantly correlated. The amount of cross-talk between degrees of freedom did not change with the number of DOFs that had to be controlled. For half the combinations cross-talk even remained the same in the conditions without any visual information on the irrelevant DOFs. Therefore, it seems that cross-talk mainly results from motor limitations of the operator. Increasing the amount of haptic information in the hand controller, probably will help the operator to distinguish the degrees of freedom more easily. This may result in a reduction of cross-talk and better control.

16. **DESCRIPTORS** Displays Feedback Manual Control Perceptual Motor Performance Tracking	**IDENTIFIERS** 3D Controls Cross-Talk Interference

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Institute: TNO Human Factors Research Institute
Group: Skilled Behaviour

Date: July 1997

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SUMMARY

A six degree of freedom (DOF) hand controller is a device that can be used for the simultaneous control of multiple axes. These kinds of control tasks are common in areas such as teleoperation. Multi-axis control may be problematic as a consequence of interference i.e., the control of a certain DOF affected the simultaneous control of another. Irrespective whether the cause of this interference lies in the operator's motor system or in his information processing system, it can be detrimental to task performance. When input on one DOF always results in undesired input on another DOF, the nature of this interference is systematic (cross-talk). The magnitude of the interference is probably affected by the number of DOFs that has to be controlled simultaneously. This was investigated in an experiment in which a compensatory tracking task was performed. In this task one DOF of a cursor in a perspective display was disturbed (externally). Subjects had to compensate this disturbance using a 6-DOF hand controller. At the same time they had to minimize input on the other (irrelevant to tracking) DOFs. It was investigated whether there were differences between tracking performance between each separate degree of freedom (X, Y, Z, Roll, Pitch, or Yaw). Furthermore, the effect of additional (irrelevant) DOFs that had to be controlled simultaneously (0, 1, or 5), was examined. With regard to the irrelevant degrees of freedom, the steering error thus was completely caused by incorrect, accidental, steering inputs. Error on the relevant DOF was a sum of this incorrect steering input and the disturbance signal.
Both these errors (expressed in RMS scores) can be used to indicate the extent to which degrees of freedom interfered with each other. In this experiment a relative RMS score was calculated by dividing the RMS score with the mean RMS error score from the 1-DOF condition (no irrelevant DOFs) that was used as a baseline condition. This way, it was possible to gain insight in the performance increment or decrement as a function of the number of DOFs that had to be controlled. Through determination of the correlations between

each combination of two degrees of freedom the extent to which systematic interference occurred was investigated.

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TNO Technische Menskunde
Soesterberg

Interferentie tussen vrijheidsgraden bij een 3D stuurmiddel

J.E. Korteling, A. Oving, M.L. van Emmerik en J.B.F. van Erp

SAMENVATTING

Met een 6 DOF hand controller is een bestuurder in staat om met één hand meer dan één as of vrijheidsgraad tegelijkertijd te besturen. Daarbij kan interferentie of (systematische) overspraak tussen vrijheidsgraden optreden, wat mogelijk beïnvloed wordt door het aantal vrijheidsgraden dat tegelijk moet worden bestuurd.
Om dit te onderzoeken werd in een experiment een compensatoire volgtaak uitgevoerd, waarbij steeds één vrijheidsgraad van een cursor in een perspectivisch display (extern) werd verstoord. De proefpersonen dienden deze verstoring te compenseren door input te leveren op de relevante vrijheidsgraad middels een 6 DOF hand controller. De compensatoire taak werd voor elke vrijheidsgraad van de 6 DOF hand controller uitgevoerd, te weten: X, Y, Z, Roll, Pitch en Yaw (drie translaties en drie rotaties). Daarnaast werd de volgtaak verricht met respectievelijk 0, 1 en 5 volgtaak-irrelevante vrijheidsgraden naast de ene volgtaak-relevante vrijheidsgraad. Hierbij kregen de proefpersonen visuele feedback over de beweging ten gevolge van hun (onbedoelde) input op deze irrelevante vrijheidsgraden. De proefpersonen konden dus respectievelijk 1, 2 en 6 vrijheidsgraden tegelijkertijd (zichtbaar) besturen. De input op de irrelevante vrijheidsgraden moest hierbij tot een minimum worden beperkt. Eventuele afwijkingen tussen de target en cursor voor deze irrelevante vrijheidsgraden waren dus geheel het gevolg van incorrecte en onbedoelde stuurbewegingen. Dit in tegenstelling tot afwijkingen voor de relevante vrijheidsgraden, die veroorzaakt worden door een externe verstoring én eventuele incorrecte stuurinput.

Door de scores uit te drukken als percentage van de gemiddelde prestatie in de conditie waarbij alleen de relevante vrijheidsgraad kon worden bestuurd werd inzicht verkregen in de prestatie af- of toename per vrijheidsgraad onder invloed van het aantal zichtbare vrijheidsgraden dat tegelijkertijd kon worden bestuurd. Door het bepalen van de correlatie tussen de stuurinput van de proefpersonen op een relevante vrijheidsgraad en de stuurinput op een irrelevante vrijheidsgraad (i.e. een combinatie van twee vrijheidsgraden) werd inzicht verkregen in de systematische interferentie (of overspraak) tussen twee vrijheidsgraden.
De resultaten van het experiment lieten zien dat er in de 1-vrijheidsgraad conditie het minst werd gepresteerd met Z bij de translatoire vrijheidsgraden en met Pitch bij de rotationele vrijheidsgraden. Dit kan te maken hebben met de weergave van de z-as (i.e. gebruikte diepte cues en mate van compressie) in het gebruikte perspectivische display. Daarnaast bleek de prestatie voor zowel een relevante vrijheidsgraad als voor een irrelevante vrijheidsgraad af te

nemen wanneer er over meerdere vrijheidsgraden tegelijkertijd visuele feedback werd gegeven ten aanzien van de geleverde input op deze vrijheidsgraden. Deze beperkingen hangen waarschijnlijk samen met capaciteitsbeperkingen in de menselijke informatieverwerking. Ten opzichte van de andere DOFs bleek deze beperking voor Z relatief substantieel, terwijl dit capaciteitseffect voor X juist relatief klein was (zowel in de relevante als in de irrelevante situatie). Verondersteld wordt dat er voor Z relatief meer aandacht en voor X relatief minder aandacht nodig is, vanwege de verschillen in de effectiviteit waarmee informatie over deze twee vrijheidsgraden werd gepresenteerd. De mate van interferentie bleek af te nemen naarmate de proefpersonen meer ervaring kregen. Dit leereffect was voor elke conditie en voor elke vrijheidsgraad even groot. Er bleek altijd sprake van systematische samenhang tussen de input op een relevante vrijheidsgraad en de input op een irrelevante vrijheidsgraad. Voor bijna de helft van de onderzochte combinaties van twee vrijheidsgraden bleek het wel of niet geven van visuele feedback de hoogte van de correlaties niet te beïnvloeden. Toename in het aantal vrijheidsgraden waarover deze feedback werd gegeven had voor geen van de onderzochte combinaties effect op de hoogte van de overspraak. De geconstateerde overspraak lijkt dan ook hoofdzakelijk een gevolg van beperkingen van het motorisch systeem van de menselijke bestuurder. Door het verbeteren van de haptische informatie die de 6 DOF hand controller levert, kunnen de verschillende vrijheidsgraden waarschijnlijk beter van elkaar worden onderscheiden, waardoor de overspraak kan afnemen.

1 INTRODUCTION

When machine, or vehicle motion is possible in three or more degrees of freedom (DOFs), several controls may be needed for operation. This can produce problems as a consequence of physical limitations of the human operator e.g., the number of limbs that can be used for control, respectively the functional and physical limitations of limb control or limb movement. Results from research into tasks involving simultaneous control of two axes or degrees of freedom indicate that integration of these DOFs in one control can facilitate operator performance, in particular when this integration is compatible with an integrated display as well (Chernikoff & LeMay, 1963; Fracker & Wickens, 1989; Korteling, 1993; Regan, 1960). Simultaneous movements in different DOFs can be made and displayed with control and display (as for example with a conventional computer mouse), provided that the control dynamics for the different DOFs are of the same order, e.g., velocity control for all axes (Chernikoff & LeMay, 1963; Fracker & Wickens, 1989).

Integrating the necessary degrees of freedom in one control (and one display) may also be advantageous to tasks in which three or more DOFs have to be controlled continuously. This is common in areas such as *remote manipulation* or *teleoperation* in which vehicles, machines, or other devices (e.g., a robot arm) have to be controlled by a physically remote operator (Buiël & Breedveld, 1995; McKinnon & Kruk, 1991). Other applications for integrated controls with more than three DOFs could be camera control for either unmanned vehicles, or TV or motion picture industry, control of excavators, cranes, or an air-to-air refuelling boom on a refuel-aircraft, cursor control in 3D-CAD/CAM environments, telesurgery, and computer and video games. An example of such an integrated control is a hand controller with six degrees of freedom. With this "joystick", all six DOFs of (graphical) objects (viz., 3 translations and 3 rotations) can be manipulated simultaneously using only one hand (Burdea & Coiffet, 1994; McKinnon & Kruk, 1991; Siva, Dumbreck, Fischer & Abel, 1988). Examples of other types of integrated controls are a *master-slave* system, in which a replica (master; possibly scaled to true size), is used to control a multiple-axis system (slave), or a 6 DOF hand tracker that can be used to translate hand movements directly into system movements (Burdea & Coiffet, 1994; Siva et al., 1988). Compared to these controls, the control area of a hand controller is small. Therefore, its manipulation is probably less fatiguing for the human operator. Besides, a hand controller is compact and light-weighted, hence easy to displace or transport.

Several demands can be made with respect to a 6 DOF hand controller (Siva et al., 1988). Among other things, the human operator has to be able to control the apparatus on one or several axes at a time without effecting other (task-irrelevant) axes too much. There is a possibility, however, that performing a task that allows for the control of six degrees of freedom with such a hand controller is complicated by interference between different movements (DOFs) caused by limitations of the operator's motor system and his information processing capabilities. This would negatively affect task performance. Additionally, interference can have a more systematical character, i.e., control movements on one axis

correlate (partially) with control movements on another axis. This so called *cross-talk* (interference between DOFs) is a phenomenon that occurs mainly with integrated controls (Fracker & Wickens, 1989; Korteling, 1993). Another factor affecting task performance is the number of degrees of freedom that can be controlled by the operator simultaneously. Since it is supposed that the capacity of the human information processing system is limited (Wickens, 1992), it could be expected that control problems arise when the number of axes to be manipulated simultaneously increases. Consequently, task performance may deteriorate because of this increasing cross-talk. For integrated controls, such as the above-mentioned hand controller, a maximum of six degrees of freedom is available. Therefore, task performance may be affected negatively if not all six axes are needed at the same time. Besides, performance on each degree of freedom can be different because of differences in the visual information displayed, and differences in the control between the degrees of freedom.

The continuous control of a system can be considered as a tracking task in which the development of system parameters over time has to be followed and the control actions of the operator have to be matched to the task goal. With regard to tracking, two display types are distinguished: a pursuit display and a compensatory display (Poulton, 1974; Sanders & McCormick, 1992; Wickens, 1992). In a pursuit display, the target and cursor are displayed separately and independently whereas a compensatory display only shows the difference between target and cursor. Usually tracking performance is superior with pursuit displays (Andre & Wickens, 1992; Poulton, 1974; Wickens, 1992). This advantage originates mainly from the fact that pursuit displays enable the operator to perceive the cause of a difference between target and cursor. Differences can originate from target movement, cursor movement (disturbances), or incorrect steering actions of the operator. With a compensatory display it is not possible to distinguish visually between these causes (Knight, 1987; Wickens, 1992). As a consequence, the feedback concerning possible error or interference is not very clear. Therefore, compensatory displays are expected to suffer more from interference or cross-talk than pursuit displays.

The present experiment investigated interference between the six degrees of freedom of a 6-DOF hand controller, and to what extent this possible interference occurred between combinations of degrees of freedom. The nature of the possible interference (systematical or non-systematical) was also examined. Systematical interference was considered as cross-talk. At the same time, the effect of the number of simultaneously controlled DOFs of a cursor on task performance was investigated.

For this occasion, a compensatory tracking task was used because of its higher interference between the degrees of freedom. In all task conditions only one out of six cursor DOFs was disturbed for which subjects had to compensate. Although only one DOF was relevant to the tracking task, subjects could also generate input on the other five (irrelevant) degrees of freedom. In the experiment, visual feedback was always provided concerning the relevant DOF. In two other conditions, there was additional visual feedback on 1, or 5 irrelevant degrees of freedom.

In order to determine the extent of interference between degrees of freedom, for each DOF performance was measured both when the DOF was relevant and when it was irrelevant to tracking performance. It was expected that performance on both relevant and on irrelevant degrees of freedom would decrease during simultaneous multi-axis control. Main task goal was to fix cursor position and orientation on a (stationary) target. Subjects had to compensate cursor disturbances for one (relevant) DOF and minimize the input on other (irrelevant) DOFs (with or without visual feedback). Hence, cursor displacement on the irrelevant degrees of freedom must be caused completely by the subject's incorrect steering inputs. Tracking task performance and the extent to which incorrect steering inputs are made can be considered as an indication for the extent of interference between degrees of freedom.

2 METHOD

2.1 Subjects

The subject group was composed of 18 right-handed males aged between 20 and 27 (mean age 23.1, SD 2.0 years). This homogeneous composition was chosen because performance on spatial tasks is rather sensitive to sex and age (Anastasi, 1958; Gleitman, 1991; Korteling, 1993). All subjects had normal or corrected-to-normal visual acuity. No colour-deficient subjects participated. Subjects with previous experience in similar experiments or with experience with 3D-controls were excluded from the experiment. Subjects were paid for their participation in the experiment.

2.2 Experimental task

The experimental task was a compensatory tracking task in which the subjects were required to fix cursor position and orientation, on the position and orientation of a non-moving target using a 3D-control. The subjects had to correct the deviations between cursor and target that were caused by a disturbance of the cursor. This disturbance signal was unpredictable to the subjects but it affected only one DOF during a trial. Subjects had to perform the task controlling 1, 2, or 6 cursor DOFs. This means that in situations with 2-, or 6-DOF control, the subjects could also control the cursor in degrees of freedom that were not disturbed, thus in fact, irrelevant to the tracking task (1 and 5 irrelevant DOFs, respectively). With respect to these irrelevant DOFs, the cursor had to be kept in the same position and at the same orientation as the target. Subjects thus had to minimize the inputs on those degrees of freedom (or rather, they had to avoid to give any input on those DOFs completely).

2.3 Display

The display was a monoscopic, perspective 2D-display (also called 2½D-display). On the screen, two differently coloured cubes were displayed: a red one as the cursor, and a green target. Both cubes were constructed of six planes, each with different levels of brightness and saturation. This way the occurrence of confusion about the orientation of the cursor-cube was made less probable. Because the target was stationary, only the front and upper plane were displayed with different brightness and saturation levels. To provide the subjects with more depth-information, the cubes were depicted in a tunnel-like environment consisting of four walls with a brick texture against a background without texture. The dimensions of this environment were $15 \times 4 \times 3.5$ m and the dimensions of the both cubes in the environment were $1 \times 1 \times 1$ m (depth$\times$width$\times$height). The centre of the stationary target was positioned at a distance of 7.75 m from the background, at a height of 1.4 m above the "tunnel floor", precisely in the centre of the environment. In the display the difference in depth between target and cursor could be derived from differences in (relative) size. Another depth cue was provided by interposition. The target-cube, however, was made partially transparent so that the cursor-cube was still visible all the time, even if it was located behind the target-cube.

Initially, position and orientation of the target and cursor were identical. The three axes of the cursor-cube (an axis is positioned perpendicular to a plane and runs through two facing planes) were always the axes around which the three rotations took place. This way, the rotational axis always parallelled the matching axis of the cursor, hence, the perception of the rotational movements was optimal (Pani, William & Shippey, 1995).

The display was presented with a 10° angle of elevation on the screen by rotating the direction-of-view of the projection centre (the "eye" of the computer; McGreevy & Ellis, 1986) downwards with 10°. In other words, the centre of the screen was depicted at a height of 3 m in the graphical environment. This way, better information about position and orientation of the target was available because not just the front plane but also the top surface of the target cube was visible all the time. This means that the y- and z-axis were displayed with compression. All above-mentioned dimensions refer to the projection and convey the proportions of the displayed objects in relation to each other.

A second display, directly positioned next to the above-mentioned display, was used to present a stylized cube (see § 2.8, Figure 1). This display functioned as a help display; it informed the subjects about which DOF of the cursor was distorted. The DOF concerned was indicated by a white arrow. Furthermore, information about possible irrelevant degrees of freedom was presented; these were pointed out by green arrows. The information was displayed during the entire trial. It appeared on the screen about 5 seconds before each trial started. This way the subjects always had task relevant information at their disposal.

2.4 Trials

Each trial of the experimental task lasted 64 seconds of which the first 4 seconds were not used in the final analysis. In these 4 seconds, the disturbance signal gradually faded-in to allow the subjects to adapt to it. This was effectuated by multiplying the disturbance signal with a factor $t/120$, (t varied from 0 to 120). After 4 seconds t had reached the value 120 so that the disturbance was added completely and unfiltered to the DOF that had to be controlled.

To create the disturbance signal a semi-random signal (pink noise) was used. In Appendix A, the spectral analysis with a histogram of the absolute amplitudes of the signal is shown. During each trial the same disturbance signal was used. The starting point of the signal, however, was randomly determined per trial. The disturbance signal had a duration of 60 seconds such that the first 4 seconds were used twice.

2.5 Independent variables

In the experiment three independent variables were manipulated within subjects: *degree of freedom* (6 levels), *number of visibly controllable DOFs* (3 levels), and *repetition* (2 levels).

Degree of freedom

It was investigated if performance differed between the 6 DOFs (in the relevant as well as in the irrelevant situation)

Number of (visibly) controllable DOFs

In the experimental task always only one DOF was relevant whereas the number of irrelevant DOFs that could be controlled simultaneously (i.e., on which subjects received visual information) was varied (0, 1, or 5 irrelevant degrees of freedom). The experimental task was thus performed with 1, 2, or 6 DOFs in which the cursor could be controlled. Note that in the 1, and 2 DOF condition, subjects could still manipulate the *hand controller* in all six DOFs because no hardware modifications were made to the hand controller. For each trial the input on the (irrelevant) DOFs that were not controlled (i.e., on which subjects received no visual feedback) was ignored by the image generating system (but in the 1-DOF condition these inputs were recorded anyhow).

Repetition

To investigate the possible effects of fatigue or practice, all trials were repeated in a second block consisting of the same trials in the same order.

In the 1-DOF condition each degree of freedom was disturbed once, resulting in 6 trials. Subjects had to control the cursor in the same DOF that was disturbed. Because in the 2-DOF condition subjects could also control an extra (task-irrelevant) DOF, each trial was presented five times, each time with another irrelevant DOF added to the task-relevant DOF. This resulted in 30 (6×5) trials. The third condition, in which 6 degrees of freedom were controlled, was presented 6 times, each DOF was disturbed once while the remaining DOFs were irrelevant. Over these three conditions, this resulted in a total number of 42 different trials. Because each trial was performed twice, the total number of experimental trials was 84.

2.6 Dependent variables

Task performance (RMS-error) on a degree of freedom in the 1-DOF condition was considered as a baseline score indicating the subject's ability to correct deviations between cursor and target. This baseline score was mediated over the two blocks. Consequently, the RMS-error scores for each DOF in the other conditions (relevant as well as irrelevant) were divided by the individual baseline score and expressed as a percentage. Based on these calibrated RMS-error scores, a better insight could be obtained in the development of task performance for each DOF within the different conditions. A calibrated RMS-error score of more than 100% indicated superior performance (compared to the baseline score), the reverse is true for scores below 100%.
An additional effect of the rescaling was that translations and rotations could now be compared whereas originally they were expressed in metres and degrees, respectively.

To determine the extent of cross-talk (systematic interference) between DOFs, for each subject the absolute product moment correlation (PMC) between the input on a task relevant DOF, and the input on each irrelevant DOF (yielding a total of 30 combinations altogether) was calculated. Because the 6 DOFs have different characteristics, (e.g., translations and rotations) it may be assumed that the sign of the correlation is determined by arbitrary individual characteristics rather than systematic factors (Korteling, 1993). This was confirmed upon inspection of the data in which the sign of the correlation differed for different subjects. Furthermore, the mean score of the two blocks (repetition) was calculated because a first analysis of the correlations showed no main, or interaction effects for repetition.

Insight in the intrinsic (motor) correlation between two degrees of freedom was gained from the correlations 1-DOF condition. In this condition, subjects received no visual feedback with regard to the irrelevant DOFs. As a consequence, they could not compensate the self-generated error on these DOFs. Therefore, in this condition, the proportion of common variance (squared correlations) could be considered as an unbiased indication of the motor correspondence between each of the hand controller's six degrees of freedom (Fracker & Wickens, 1989; Meerling, 1988).

2.7 Data-storage and statistical analysis

In each condition, subjects could generate all possible movements in all degrees of freedom with the 6 DOF hand controller. For each trial, the inputs on each DOF, together with the disturbance signal, and the trial specifications were recorded with a sample rate of 30 Hz. The image generation system, however, only used the input of the degrees of freedom that were specified by the condition (viz. 1, 2, or 6). Dependent on the condition, input on remaining DOFs (5, 4, or 0, respectively) was ignored by this system. From these data, Root Mean Square (RMS) errors were calculated (Poulton, 1974). Calculation of this measure is based on the differences between target and cursor in sequential moments of time. For each trial, an RMS-error was calculated for the task-relevant DOF and in the 2-, and 6-DOF condition for the irrelevant DOFs as well. Because of the number of combinations, in the 2-DOF condition each DOF (relevant and irrelevant) was controlled five times. Therefore, a *mean* RMS-error score was calculated for each subject in these conditions. The same procedure was followed for the irrelevant DOFs that were also repeated five times in the 6-DOF condition.

At first, the RMS-error scores for the relevant degrees of freedom, in the 1-DOF condition were analysed. Translations and rotations were treated separately. For both types of DOF, a 3 (DOF) $\times$ 2 (block) ANOVA was conducted. These scores were used to gain insight in the possible differences between the degrees of freedom concerning the mean baseline score. The calibrated RMS-error scores for the tracking task (relevant DOFs) were analyzed with a 6 (DOF) $\times$ 3 (number of visibly controllable DOFs) $\times$ 2 (block) ANOVA. For the analysis of the calibrated RMS-error scores on the irrelevant DOFs, the same analysis was conducted except for the fact that only 2 levels existed with regard to the number of controllable degrees of freedom. Because in the 1-DOF condition no visual feedback at all was provided concerning the input on irrelevant DOFs, this condition was excluded from that particular analysis.

Before the analyses were conducted, all observations with a deviation of more than three standard deviations away from the mean (per DOF, per condition, and per block) were removed and substituted by the mean value. The mean correlations concerning the systematical interference were analyzed with a 3 (number of DOFs to be controlled) $\times$ 30 (possible combinations of two DOFs) ANOVA.

All analyses were conducted with generally accepted, commercially available statistical packages: STATISTICA (version 5.0) and SPSS/PC+ (version 4.0). All post-hoc tests (Tukey's HSD) were conducted with STATISTICA (v. 5.0) and TKTOETS (v. 1.0). In all analyses an α of 0.05 was regarded as the limit for significant results. All analyses were based on means.

2.8 Procedure

Subjects participated in the experiment in pairs. When one subject was working on the task, the other subject rested. The experiment consisted of two blocks. In each block, the same 42 trials were presented. The total number of 84 trials was performed by the subjects in 7 turns of 12 trials. After each trial, the experimenter waited for about five seconds to start the next one. Between the sixth and seventh trial there was a pause of about 12 seconds. Subjects traded places after each turn. To prevent sequence-effects, the order of the conditions (with regard to the number of DOFs to be controlled) was balanced. The trials for a certain condition were presented sequentially, in which the order of the 6 trials in both the 1-, and the 6-DOF conditions was balanced over the 6 subjects to which the conditions were presented at the same moment in the experiment. Because of the large number of combinations in the 2-DOF condition, the sequence of the trials was randomized for each subject in that condition. The sequence of trials in both blocks (repetition) was the same.

Before the experiment started, the subjects received a written introduction on the experimental task and the 6-DOF hand controller. Furthermore the information displayed on the second screen was verbally explained by the experimenter. Subsequently the subject was allowed to manipulate the red cursor-cube for a period of 30 seconds using the hand controller. The target was not presented during that time. The six degrees of freedom of control and cursor (see Figure 1) were directly coupled. This meant that all cursor movements made by the subjects resulted in similar cursor movements on the screen. After that, the subjects got the opportunity to practice on the experimental task. Training on all 42 trials was not possible, therefore, only the 6 different trials from the 6-DOF condition were presented as practice trial. Each of these practice trials lasted 30 seconds. After the subjects were allowed to ask possible questions, the experiment started.

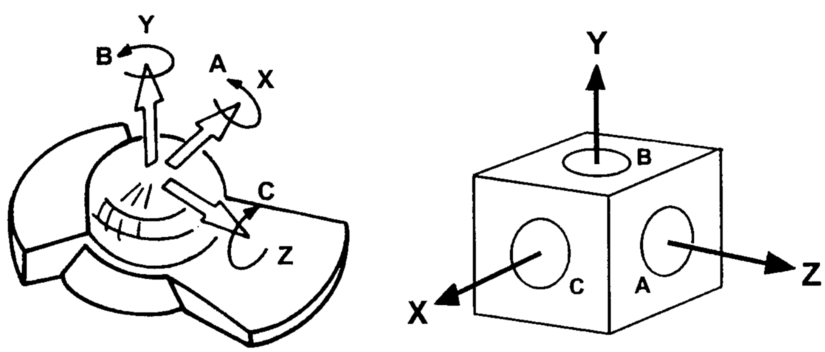

Fig. 1 The 6 degrees of freedom of the used hand controller and the cursor (movements in the opposite directions of the arrows were also possible). Movements along an axis or DOF with the hand controller resulted in identical movement along the same axis of the cursor on the screen (A = Pitch, rotation around x-axis; B = Yaw, rotation around y-axis; C = Roll, rotation around z-axis).

2.9 Instrumentation

The experiment was conducted with the Space Mouse® (specification in Appendix B). This is a commercially available 6 DOF control. As can be seen in Figure 1, it allows for translations along x-, y-, and z-axis and rotations around these axes viz. pitch, yaw, and roll respectively. The control consists of a flat, circular button that is mounted to a stationary platform. For better grip, a small ball with a diameter of 7 cm. was placed over this button. The application of power/ torsion to the ball results in movements of the object that has to be controlled. Forces will result in a small displacement of the ball relative to the platform. For translations, this displacement is about 1.5 mm. and for rotations it is about 4°. Although very small, this displacement can be perceived very well. Besides, the ball is *spring-centred* which means that it returns to its neutral (central) position as soon as no force, or torsion is applied to it. With such a control, performance can be better than with an isometric (force) 3D-control because it gives more proprioceptic feedback (Zhai, 1993; Zhai & Milgram, 1993). With a spring-centred control, both the position of the control (and the resulting position of the used limbs) and the applied force provide information on the input (Knight, 1987; Poulton, 1974). The hand-controller was horizontally placed and mounted to an arm-rest on a table surface. The force/movement ratio of the Space mouse is 3N/mm for translations. In the experiment the cursor was manipulated with position control with a maximum absolute radius of 85 cm for translations and 50° for rotations. This enabled the subjects to compensate for all presented disturbances in the experiment (the maximum amplitude of the disturbance signal was 67.5 cm for translations and 40.5° for rotations). Position control was used because the correcting of a self generated error on the irrelevant degrees of freedom is easier with this kind of control, and therefore gives a better indication of involuntary steering movements.

The image generation system used was an Evans & Sutherland ESIG-2000 system (specification in Appendix C). The generated images were displayed on a 19-inch Mitsubishi colour monitor (type HL7955SBK). The display was positioned vertically on eye-height. The area of the display that was utilized for projection was 36 cm horizontally × 26 cm vertically. The centre of the projection was placed on a distance of 45 cm from the screen. This resulted in an image angle of 43° horizontally × 33° vertically. During the experiment the subjects were seated at a distance of 50 cm from the display.

The second screen was a 14-inch SVGA colour monitor with a maximum refresh rate of 60 Hz. Images on this screen were generated by a 80486DX2-66 pc. The Space Mouse was connected to a second 80486DX2-66 pc that also passed on the disturbance signal to the image generation systems and was responsible for the data storage as well. A third computer (80486DX-33 pc) was used as a clock to synchronize update- and sample frequency of the total configuration at 30 Hz.

3 RESULTS

In this chapter the results with regard to the analyses of the different dependent variables are discussed separately. First, the RMS-error scores that were used to determine the baseline score, will be discussed for each degree of freedom. Next, tracking performance on the relevant DOFs, and the irrelevant DOFs will be showed, respectively. Finally the results concerning the cross-talk between DOFs will be presented.

3.1 Baseline scores

An analysis of the RMS-error for the relevant translatory DOFs (X, Y, and Z) in the 1-DOF condition, showed a main effect for DOF [$F(2,34)=7.10$, $p<0.01$]. The post-hoc analysis of this effect revealed that the mean RMS-error for Z deviated significantly from the mean X, and Y scores. Furthermore, an effect for block (repetition) was found [$F(1,17)=20.3$, $p<0.001$]. As can be seen in Table I, performance in the second block was better for all types of translations. Although this seems also to be the case for the rotations, these differences were not significant. There was, however, a significant main effect for (relevant) rotational DOF, [$F(2,34)=3.82$, $p<0.05$]. Roll performance was superior over Pitch control according to the post-hoc analysis. Surprisingly there was no difference between Yaw and Pitch although a trend towards significance was visible ($p=0.07$). No interactions between DOF and block were found. With respect to the translations, this means that the previously mentioned effect of block was the same for all three kinds of translations.

Table I Mean RMS-error score per DOF in the 1-DOF condition. The degrees of freedom are grouped according to the 2 different types: translation (in meters) and rotations (in degrees).

Block	Translations (RMS-error in meters)			Rotations (RMS-error in degrees)		
	X	Y	Z	Roll	Pitch	Yaw
1	0.210	0.237	0.260	13.19	15.20	13.13
2	0.173	0.176	0.227	12.49	13.12	12.74

3.2 Relevant degrees of freedom

In this section, control performance on the 1-DOF tracking task (relevant DOF) is treated as a function of: the number of DOFs that the subject could control on the screen (i.e., 1 relevant DOF **and** 0, 1, or 5 irrelevant DOFs); block; and the specific relevant DOF.

The analysis revealed a main effect of the number of (visibly) controllable DOFs [$F(2,34) = 76.8$, $p < 0.001$]. Figure 2 shows that 1-DOF tracking performance deteriorated when the number of additional (irrelevant) DOFs increased. A post-hoc Tukey test confirmed this finding: for all three conditions the difference was significant. Furthermore, performance during the second block was better than during the first [$F(1,17) = 28.7$, $p < 0.001$], as can be seen in Figure 2. The interaction between block and number of DOFs to be controlled was not significant, just as the interaction between block and relevant DOF.

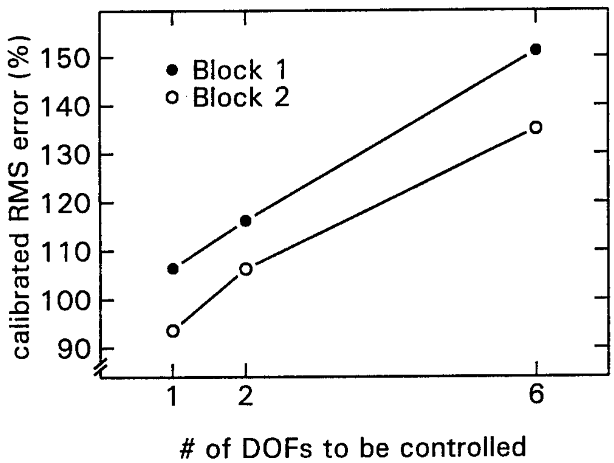

Fig. 2 Mean percentage RMS-error on the relevant DOFs as a function of the number of DOFs to be controlled, and block. This percentage was determined relative to the individual mean RMS-error per relevant DOF in the 1-DOF condition.

A third main effect concerned the factor "relevant degree of freedom" [$F(5,85) = 10.9$, $p < 0.001$]. It was found that the addition of extra (irrelevant) DOFs that had to be controlled affected Z-axis performance more than it did affect performance on any other DOF (see Figure 3). This score was shown to differ from all the other DOFs scores by a post-hoc Tukey test. There were no differences found between the other degrees of freedom.

Furthermore, an interaction between relevant DOF and the number of DOFs to be controlled was found [$F(10,170) = 13.1$, $p < 0.001$]. As can be seen in Figure 3, the relative tracking error increased for each relevant DOF in the 6-DOF condition. This difference was extremely large for Z. Post-hoc analysis of this effect showed that the differences between the 1-DOF and 2-DOF conditions were not significant except for Z. The 6-DOF condition was performed worse for each relevant DOF except for X. It was also found that there were no significant differences between the error scores in the 2-DOF condition.

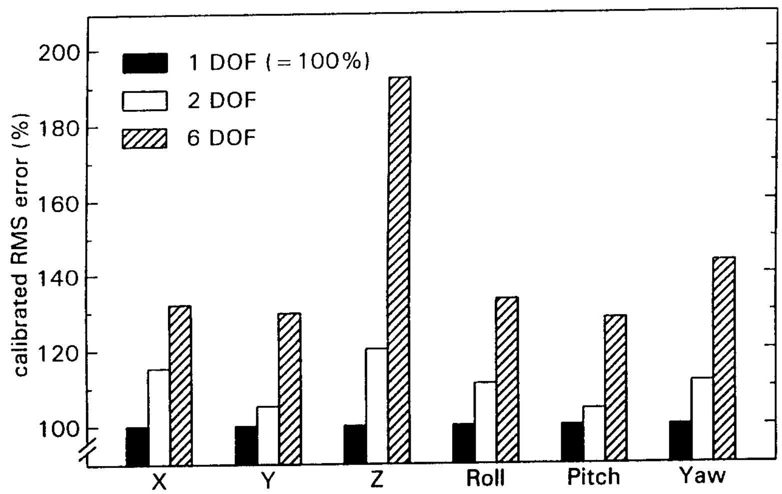

Fig. 3 Mean percentage RMS-error (relative to 1-DOF condition) per relevant DOF and as a function of the number of DOFs to be controlled.

3.3 Irrelevant degrees of freedom

In this section, the control performance on the irrelevant DOFs is discussed. This involves the differences between the specific irrelevant DOFs, and to the interactions with block, and with total number of DOFs that was to be controlled.

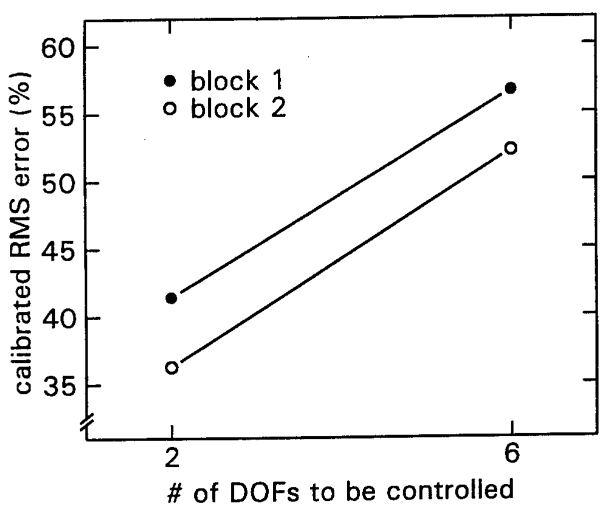

Fig. 4 Mean percentage RMS-error for the irrelevant DOFs, as a function of the number of degrees of freedom to be controlled, and block. This percentage is determined in relation to the individual, mean RMS-error score on each relevant DOF in the 1-DOF condition.

The 2×2×6 ANOVA for number of DOFs that had to be controlled, block, and irrelevant DOF, showed a significant main effect for number of DOFs to be controlled [$F(1,17)=45.3$,

$p<0.001$]. In the 2-DOF condition (1 irrelevant DOF), the input subjects gave on the irrelevant DOF was smaller than in the 6-DOF condition (5 irrelevant DOFs). In other words, the addition of irrelevant DOFs, leads to an increase of task irrelevant input (see Figure 4). From Figure 4 it can also be seen that there was a training effect. Subjects had a smaller relative RMS-error on the irrelevant DOFs in the second block [$F(1,17)=6.42$, $p<0.05$]. Furthermore, no significant interactions between the variable block and other factors were found, i.e., with regard to this training effect there were no differences between conditions (number of DOFs to be controlled) or irrelevant DOFs.

Again a significant main effect of irrelevant DOF was found [$F(5,85)=35.4$, $p<0.001$]. A post-hoc analysis of this effect revealed that the difference between Z, and the other five DOFs caused this significance (see Figure 5). Other significant differences were found between X, and Y and Yaw with superior performance on X. Also from Figure 5 it can be seen that the factor "DOF" interacted with the "number of DOFs that had to be controlled" [$F(5,85)=20.5$, $p<0.001$]. In the post hoc analyses no differences were found between the two conditions for X, Roll, and Yaw. With regard to Y, Z, and Pitch, it was found that the calibrated RMS-error increased in the 6-DOF condition compared to the 2-DOF condition. In this condition, the percentage RMS-error was found to increase most when the Z-axis was added as irrelevant control axis. The smallest increase resulted from the irrelevant X-axis. Both irrelevant DOFs differed from each other as well as from the other DOFs. (It has to be noted that the difference between X, and Pitch failed to reach significance in the 2-DOF condition.) The same effect was observed in the 6-DOF condition. With regard to the other DOFs, no differences were found.

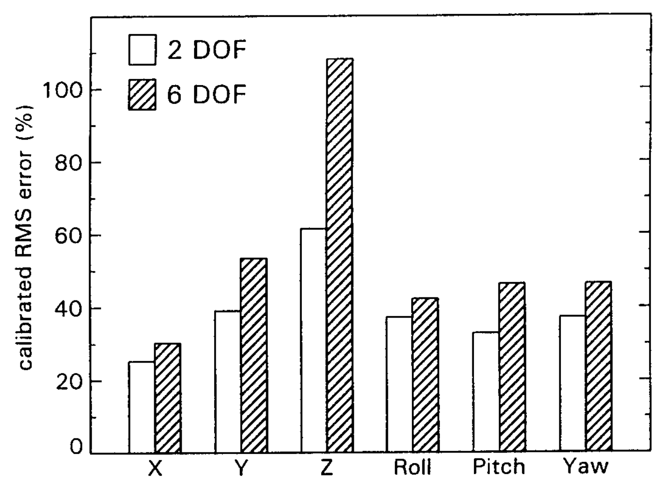

Fig. 5 Mean percentage RMS-error for each irrelevant DOF and as a function of the number of DOFs to be controlled.

3.4 Cross-talk

To gain insight in the extent to which the cross-talk was determined by interference, for each subject, the absolute product-moment-correlation (PMC) between input on the relevant DOF and input on each irrelevant DOF was calculated resulting in a total of 30 combinations (mediated over the two blocks). As a result of the large number of data samples used to calculate these correlations (1800 samples), all correlations larger than 0.09, are significantly different from 0 ($p<0.01$).

With regard to the strength of the correlations, values between 0.5 and 0.7 are considered substantial (25-50% of common variance), whereas correlations lower than 0.5 are weak (less than 25% of common variance). Table II presents the mean absolute correlations between input on the relevant DOF and input on each irrelevant DOF plus the proportion of common variance. Notice that in the 1-DOF condition, the subject's input on the irrelevant DOFs remained invisible in the display because it was neglected by the image generation system. Therefore, in this condition, the proportion of common variance can be considered as an unbiased indication of the motor correspondence between the hand controller's six degrees of freedom. The correlations, and proportions of common variance of the 2-DOF—and the 6-DOF condition, can be found in Tables III and IV, respectively.

Table II Mean absolute correlations (r), and proportion of variance accounted for (r^2) between input on the relevant DOF, and the (non-visible) input on the irrelevant DOFs in the **1-DOF** condition.

Irrelevant degrees of freedom	**X**		**Y**		**Z**		**Roll**		**Pitch**		**Yaw**	
Tracking task degrees of freedom	r	r^2	r	r^2	r	r^2	r	r^2	r	r^2	r	r^2
X	*	*	0.41	0.17	0.33	0.11	0.63	0.40	0.29	0.08	0.39	0.15
Y	0.39	0.15	*	*	0.35	0.12	0.34	0.12	0.42	0.18	0.37	0.14
Z	0.43	0.18	0.41	0.17	*	*	0.34	0.12	0.55	0.30	0.33	0.11
Roll	0.63	0.40	0.36	0.13	0.32	0.10	*	*	0.33	0.11	0.58	0.34
Pitch	0.37	0.14	0.28	0.08	0.69	0.48	0.36	0.13	*	*	0.41	0.17
Yaw	0.52	0.27	0.34	0.12	0.38	0.14	0.37	0.14	0.41	0.17	*	*

The ANOVA on height of the correlation as a function of DOF combination, and number of (visibly) controllable DOFs shows that the correlations between the DOFs differ in the three conditions [$F(2,34)=118.1$, $p<0.001$]. From a post-hoc Tukey test this difference was shown to be significant, with the lowest mean correlation (0.204) found in the 2-DOF condition, followed by the mean correlation of the 6-DOF condition (0.272) and that of the 1-DOF condition (0.412). From this it turns out that the systematic interference increased somewhat

with an increase in visibly controllable (irrelevant) DOFs, and increased substantially when visual feedback concerning the input on the irrelevant DOFs was absent.

Table III Mean absolute correlations (r), and proportion of variance accounted for (r^2) between input on the relevant DOF, and the (visible) input on the irrelevant DOFs in the **2-DOF** condition.

Irrelevant degrees of freedom	X		Y		Z		Roll		Pitch		Yaw	
Tracking task degrees of freedom	**r**	**r^2**	**r**	**r^2**	**r**	**r^2**	**r**	**r^2**	**r**	**r^2**	**r**	**r^2**
X	*	*	0.17	0.03	0.18	0.03	0.22	0.05	0.17	0.03	0.11	0.01
Y	0.15	0.02	*	*	0.28	0.08	0.17	0.03	0.24	0.06	0.17	0.03
Z	0.20	0.04	0.25	0.06	*	*	0.15	0.02	0.19	0.04	0.12	0.01
Roll	0.25	0.06	0.16	0.03	0.31	0.10	*	*	0.16	0.03	0.29	0.08
Pitch	0.17	0.03	0.20	0.04	0.46	0.21	0.14	0.02	*	*	0.18	0.03
Yaw	0.23	0.05	0.16	0.03	0.20	0.04	0.19	0.04	0.24	0.06	*	*

Besides, an effect of combination of DOF was found [$F(29,493)=8.78$, $p<0.001$]. This factor also turned out to interact with the number of DOFs that had to be controlled. For the post-hoc analysis of this interaction, for each condition (number of DOFs to be controlled), the differences between the five possible combinations of an irrelevant DOF with a certain relevant DOF were investigated. Besides, for each combination, the differences between the three conditions were investigated. The data concerning this interaction can also be found in tables 2, 3, and 4. References to the combinations in the text below denote the relevant DOF first, and then the irrelevant DOF.

Table IV Mean absolute correlations (r), and proportion of variance accounted for (r^2) between input on the relevant DOF, and the (visible) input on the irrelevant DOFs in the **6-DOF** condition.

Irrelevant degrees of freedom	X		Y		Z		Roll		Pitch		Yaw	
Tracking task degrees of freedom	**r**	**r^2**	**r**	**r^2**	**r**	**r^2**	**r**	**r^2**	**r**	**r^2**	**r**	**r^2**
X	*	*	0.26	0.07	0.28	0.08	0.29	0.08	0.19	0.04	0.26	0.07
Y	0.22	0.05	*	*	0.33	0.11	0.16	0.03	0.26	0.07	0.19	0.04
Z	0.36	0.13	0.38	0.14	*	*	0.24	0.06	0.24	0.06	0.24	0.06
Roll	0.34	0.12	0.20	0.04	0.24	0.06	*	*	0.18	0.03	0.41	0.17
Pitch	0.27	0.07	0.22	0.05	0.47	0.22	0.31	0.10	*	*	0.26	0.07
Yaw	0.32	0.10	0.24	0.06	0.31	0.10	0.21	0.04	0.29	0.08	*	*

In the 1-DOF condition, the correlation between X and Roll (r=0.63; see Table II) differed from the correlations of the other combinations in which X was the relevant DOF. The subject's steering input on X, thus, correlated strongest with the non-visible input on Roll. In other words, while giving translational inputs along the x-axis, 40% of this input resulted in rotations around the z-axis. With regard to Z, significant differences were found between Z-Pitch (r=0.55) on the one hand, and Z-Roll and Z-Yaw (r=0.34 and r=0.33, respectively) on the other hand. The highest correlations with regard to Roll as the relevant DOF, were found with Roll-X (r=0.63) and Roll-Yaw (r=0.58), in which these two combinations differed significantly from the other three combinations. Besides the reasonably high correlation between X and Roll, there also turned out to be a similarly high correlation between Roll and X. The control of one of these two DOFs thus partly resulted in systematically correlated movements on the other DOF. The same was true for the combinations Z-Pitch, and Pitch-Z (r=0.69). This last combination differed significantly from the other four combinations in which Pitch was the relevant DOF. The mean correlations for X-Roll, Roll-X, as well as for Pitch-Z were found to differ significantly from all correlations below 0.45. For Roll-Yaw, this was true for correlations below 0.39, whereas this borderline score was 0.36 for Z-Pitch. The combinations with either Y, or Yaw as relevant DOF did not show any significant differences as far as cross-talk was concerned, even though the correlation for Yaw-X (r=0.52) was reasonably high.

In the 2-DOF condition, the only difference that reached significance was between Pitch-Z (r=0.46; the highest score in Table III), and the other combinations with Pitch as relevant DOF. Despite the fact that subjects received visual feedback on their inputs on Z (which should have helped them to limit their movements on this irrelevant DOF), the input on Z still varied reasonably systematically with steering input on Pitch. For the other five (relevant) DOFs, no significant differences were found with regard to interference with the irrelevant DOFs. The correlation between Pitch and Z, significantly differed from all other correlations below 0.28.

Something similar was seen in the 6-DOF condition (see Table IV). There was a significant difference between the combination Pitch-Z (r=0.47), and all correlations below 0.29. Furthermore, there was a difference between Roll-Yaw (r=0.41) on the one hand, and Roll-Y and Roll-Pitch on the other hand meaning that in this condition, Roll-Yaw was bothered more by cross-talk than the other two combinations.

The analysis of the differences between the conditions on each combination revealed no differences between the 2- and 6-DOF conditions, that is, the number of (controllable) irrelevant DOFs did not affect the amount of interference. There was however a significant difference between the 1-DOF condition and the 6-DOF condition for the combinations X-Roll and Roll-X, Pitch-Z, and Z-Pitch, and the combination Yaw-X. Moreover, these combinations also differed significantly between the 1- and 2-DOF condition. That is, the fairly high correlations of the combinations in the 1-DOF condition, were significantly reduced as soon as the subjects could see their input on the irrelevant DOFs. It has to be

noted that the correlation between Pitch and Z, still remained rather high even with the visual information in the 2- and 6-DOF conditions.

Apart from the above-mentioned combinations, another 11 combinations showed significant differences from the 1-DOF condition in the 2-DOF condition: X-Y, X-Yaw, Y-X, Y-Yaw, Z-X, Z-Yaw, Roll-Y, Roll-Yaw, Pitch-X, Pitch-Roll, and Pitch-Yaw. For the remaining 14 combinations, the differences between the conditions were not significant, i.e., in all those conditions there was a similar level of interference.

4 DISCUSSION

The present experiment investigated the extent of possible interference between different degrees of freedom during the manipulation of a hand controller. Whereas this particular device enabled control of 6 degrees of freedom, the experiment was programmed in such a way that the number of degrees of freedom that could be manipulated simultaneously was adjustable, i.e., although subjects could always generate input on all six degrees of freedom, in some conditions the input on certain DOFs was neglected such that subjects received no visual feedback concerning this input. In the experiment, subjects had to control with visual feedback 1, 2, or 6 DOFs of a cursor while only one of this degrees of freedom was disturbed. It was expected that the interference between degrees of freedom would increase, with an increase of the number of visually controllable DOFs. The experiment also examined differences between the six degrees of freedom with regard to possible interference and cross talk.

As experimental task, a compensatory tracking task was chosen. In the experiment, each DOF was examined both when it was relevant (disturbed) and when it was irrelevant to tracking performance. For a relevant DOF, the error between cursor and target was caused by the cursor disturbance (external), and the (possible) steering errors the subject made. With regard to the irrelevant DOFs the deviation between target and cursor always was caused completely by the subject's unintended inputs. Therefore, tracking error on the irrelevant DOFs could be used as an indication of interference between DOFs. In each trial the RMS-error was calculated for the relevant and possible irrelevant DOFs. These error scores were divided by the (individual) mean RMS-error from the 1-DOF condition which was used as a baseline condition. This way, a measure was obtained that indicated each individual subject's ability to correct disturbances on a certain DOF. No absolute scores were examined.

By determining the correlation between the steering input on the relevant DOF and the steering input on each irrelevant DOF, insight was gained in the extent of structural interference (cross-talk) between two degrees of freedom. Since the subjects were not supposed to provide input on the irrelevant DOFs, the squared correlation (the amount of common variance) can be considered as an indication of the extent to which the irrelevant DOF

interfered with control of the relevant DOF. For clarity's sake it is noted that the heights of the correlations provide no information on the height of the interference but only on its systematicity.

Baseline tracking performance

The analysis of the RMS-error scores in the baseline condition (1-DOF) with regard to performance on the relevant DOF, showed that performance with regard to translations on Z (depth dimension) was worse than performance with either X or Y. This "asymmetric spatial accuracy" probably is caused by the limited representation of depth on the perspective display. The representation of three dimensions on a 2-D screen can only be based on a limited number of visual depth cues. In this experiment these cues were: interposition, texture gradient, and relative size (based on a linear perspective). Interposition is a cue that does not provide information about the distance between two objects, only that one object is in front of another (Coren, Ward & Enns, 1994). This kind of information had to be derived mainly from the relative size of the objects. However, when the cursor was in front of the target, the relative size cue was of little use because the cursor covered up the target. This may have produced additional difficulty in the perception of depth. Conversely, when the cursor was behind the target, this was probably less of a problem because the target was partially transparent.

One possibility to improve performance on the depth dimension is by changing the angle of elevation under which the 3-D environment is projected (in the present experiment this was 10°). Kim, Tendick and Stark (1991) found that an angle of elevation for presentation of 3 dimensions in a 2-D display between 30° and 75° produced the best results. The performance decrement on either side of these limits was attributed to the loss of visual information with regard to motion in depth. Further performance improvement can be obtained when extra depth cues are added to the display. The performance on the depth dimension can be considered as a sum of the effect of each separate depth cue (Coren, Ward & Enns, 1994). The addition of binocular disparity by means of a stereoscopic display, for example, was found to improve performance on the depth-dimension in spatial tasks (Kim, Tendick & Stark, 1991; Zhai & Milgram, 1994), although the difference between Z, and X and Y remained present (Zhai & Milgram, 1994).

With regard to the rotations, it turned out there was a difference between Roll and Yaw on the one hand, and Pitch on the other hand. Although the difference between Yaw and Pitch did not reach significance, the data showed a trend ($p=0.07$). Just as with Z, these results may be related to the interposition cue. A rotation around the x-axis (Pitch), causes a part of the target to be obscured by the cursor which may complicate the perception of the size of the rotation. Rotation around the z-axis (Roll) and around the y-axis (Yaw) are less susceptible to this problem because differences between target and cursor are mainly displayed in de plane through the x-, and y-axis. Therefore, less depth information is needed.

Only with respect to performance on the translations a significant training effect was found indicating that subjects still improved skills on these DOFs.

Relevant and irrelevant degrees of freedom

An increase of the calibrated RMS-error was found with regard to the relevant (disturbed) as well as the irrelevant DOFs, when the number of DOFs that could be visibly controlled increased. From this it follows that the availability of irrelevant degrees of freedom interferes with task performance. The extent to which interference occurs was determined by the number of irrelevant DOFs added to the task. For tasks that are performed with a 6-DOF controller, this interference is something to seriously take into consideration. This may be explained by the fact that the control of several degrees of freedom relies on the same perceptual-motor systems, especially because only one hand is used in control. These systems are supposedly limited in their capacity to combine the simultaneous performance of different processes. When this limited capacity has to be divided over the different (relevant, as well as irrelevant) DOFs, performance on both types will decrease (Korteling, 1994; Wickens, 1992).

The magnitude of this capacity problem differs per DOF as was shown by the significant interactions of relevant DOF, as well as irrelevant DOF with the number of DOFs that was to be controlled. Compared to the 1-DOF condition, in the 2-DOF condition tracking performance of translational disturbances along the z-axis (Z) deteriorated when an irrelevant DOF was added. Since the other degrees of freedom were not affected by the addition of a single irrelevant DOF, the significant difference between the 1-DOF, and the 2-DOF condition (from the main effect "number of DOFs to be controlled"), must be attributed exclusively to performance with Z.

In the 6-DOF condition, RMS-error on the relevant DOF did increase for any relevant DOF. For Z, this increase still was significantly larger that for the other degrees of freedom. A similar picture emerges from the RMS-error for the irrelevant DOFs. Compared to the other degrees of freedom, performance with (irrelevant) Z is worse in both the 2-DOF and the 6-DOF condition. All these problems with the control of Z, probably can be related to the difficulty with the perception of depth in the perspective display as was already noted in the discussion of the baseline scores. Because subjects had difficulty with tracking Z as well as with minimizing input on this DOF, in the present experiment Z-control presumably needed more attention than any other DOF. When this attention had to be divided, the relative decrease in available capacity was again largest for this DOF, resulting in a relatively larger decrease in performance compared to the other degrees of freedom.

The fact that the other relevant DOFs did not show any difference between the 1-DOF an 2-DOF condition, may emanate from the experimental design and (therefore) from the calculation of the scores in the 2-DOF condition. In this condition, a mean score was calculated over the five times the tracking task was performed with a specific relevant DOF, whereas in the other two conditions the task was performed only once. Since the subjects got

that much "practice" in the 2-DOF condition, it may be expected that the differences between the 1-DOF, and the 2-DOF condition are in fact larger than the differences found in the experiment. Likewise, the differences between the 2-DOF, and the 6-DOF condition, will actually be smaller than found here. This is not an issue for the differences between the *irrelevant* degrees of freedom (in the 2-DOF, and 6-DOF condition). In these conditions the mean RMS-error score was always calculated over the scores of the five trials in which a certain DOF was irrelevant.

Tracking performance with X, contrary to Z, did not suffer much from the addition of irrelevant DOFs. This was also the only DOF for which performance did not differ between the 2-DOF, and the 6-DOF condition both when X was the relevant or the irrelevant DOF. The results showed superior performance with X, especially when this DOF was irrelevant. A possible explanation for this can be found in the differences in visual feedback with regard to necessary steering input and a consequential difference in difficulty between the relevant, and irrelevant situation. When X is the relevant DOF, visual feedback is a combination of the external disturbance signal and steering input. When X is irrelevant, no disturbance is applied to the DOF, hence the feedback is easier to process. This was also reflected in the RMS-error scores: the calibrated RMS-error scores per DOF for the irrelevant DOFs for each condition, are lower than the RMS scores on the relevant degrees of freedom. It could be asserted with regard to x-axis translations that this kind of control actions were less attention demanding than the control of the other DOFs. That is, subjects were better able to keep the irrelevant input on X to a minimum than for any of the other DOFs. Tracking with X (relevant), did not show the same advantage for X, probably because of the more ambiguous visual input (i.e., the cursor was externally disturbed for the relevant DOF). An explanation for the lower attention demand of X is the fact that the x-axis , contrary to the y-, and z-axis was displayed without compression. The 10° angle of elevation, which was necessary to display the z-axis in the first place, resulted in a compressed presentation of both y-, and z-axis (although the ultimate (2-D) compression of the z-axis was reduced). Therefore, the x-axis tracking error was perceived better and could thus also be better controlled.

With regard to the irrelevant DOFs, for Roll and Yaw, no effects were found (just as for X). The relative performance for these degrees of freedom did not change irrespective of the number of irrelevant DOFs that had to be controlled. For the other three DOFs (Y, Z, Pitch) relative performance did decrease with an increase in the number of irrelevant DOFs that had to be controlled. This distinction between X, Roll, and Yaw on the one hand, and Y, Z, and Pitch on the other hand, could be related to the better visibility of object motion in the left-to-right direction as discussed above. With regard to the first three DOFs, the deviations of the cursor are predominantly in this direction. The other three degrees of freedom may have suffered from the decreased visibility in the depth dimension. Since Y, Z, and Pitch required extra attention, the addition of irrelevant DOFs lead to an increase in irrelevant input compared to the other DOFs.

A training effect was found for the relevant, as well as the irrelevant degrees of freedom. The size of this effect was the same for each DOF in each condition. The analysis of the raw RMS-error scores in the 1-DOF condition (baseline scores) only revealed a significant effect of the translational DOFs. With regard to the rotations, a trend towards significance was visible ($p=0.095$).

Cross-talk

In each condition, the combination of a relevant and an irrelevant degree of freedom lead to cross-talk although this was generally not very high (i.e., $r<0.50$). Still this means that a part of the input on the relevant DOF provided by the subject, systematically was related to the input given on the irrelevant DOF. The height of the correlation is only informative on the strength of this relation between two DOFs. Furthermore, it signals the occurrence of error (at least) with regard to the irrelevant DOF although it contains no information on the size of this error. As noted before, the visual feedback for the relevant DOF consisted of the external disturbance and the steering input, whereas the visual feedback for the irrelevant DOF only reflected the involuntary control input. Therefore, subjects lacked visual feedback with regard to the systematical relation between steering input on the relevant DOF and steering input on the irrelevant DOF. Hence, it can be stated that the systematic interference, or cross-talk, between degrees of freedom found in this experiment mainly is related to characteristics of the human motor system. The non-systematic part of interference (bias) is possibly caused by limitations of the information processing system since attention had to be divided over several DOFs. Furthermore, biomechanical motor limitations such as tremor could have been involved.

As expected, the cross-talk concerning the number of degrees of freedom that could be controlled turned out to be largest in the 1-DOF condition. In this condition the subjects had to rely on proprioceptic feedback only, to minimize input on the irrelevant DOFs. In the 2-DOF and 6-DOF condition, subjects also received visual feedback about the error on the irrelevant DOF that was supposed to help them to correct control errors. Besides subjects were instructed explicitly to minimize the errors on the (visible) irrelevant DOFs whereas this was not the case for the (invisible) input in the 1-DOF condition. In spite of all efforts, the provision of visual feedback with regard to the irrelevant DOFs, in the 2-DOF and 6-DOF condition did not suffice to eliminate all systematic interference.

No single combination of degrees of freedom was found for which the difference between the 2-DOF and 6-DOF condition was significant. This means that the amount of systematic interference was not affected by the number of irrelevant degrees of freedom that could be controlled (1 or 5). Furthermore, for half the combinations the presence or absence of visual information on the irrelevant DOFs made little or no difference for the height of cross-talk. These results confirm the idea that cross-talk mainly originates from motor limitations. Thus, whereas division of attention over DOFs increased the calibrated RMS-error, it did not substantially affect the height of the cross-talk.

The mean high correlation among DOFs in the 1-DOF condition was probably caused by the high correlations of six combinations in particular: X-Roll, Roll-X, Z-Pitch, Pitch-Z, Roll-Yaw, and Yaw-X (the first DOF of each pair is the relevant DOF). These combinations showed correlations higher than 0.5. Remarkable is that high interference occurs for X-Roll and Roll-X just as for Z-Pitch and Pitch-Z. Irrespectively of the relevance of these DOFs, input on one of them always brought about related input on the other. This can be explained by having a closer look at the way the subjects generated input on those DOFs. The left-to-right push movement needed for translations along the x-axis is very similar to the tilt movement needed to roll. Analogously, there is a correspondence between the translations along the z-axis and Pitch in the dimension "forward—backward". Without noticing it, subjects may have tilted the controller a little bit while translating it and vice versa. This pairwise interference probably can be solved by the provision of better proprioceptive and tactile feedback.

Apart from visual feedback, the handling of the 6-DOF controller also provided the subject with haptic feedback (self motion and object-related information from muscles, tendons, ligaments) regarding each DOF. Haptic information is relevant to closed-loop steering (Van Leyden, 1993) and as such, to task performance with a 6-DOF control (e.g., Zhai, 1993; Zhai & Milgram, 1993). Since the hand controller was spring-centred, the subjects also received tactile information (i.e., information with regard to pressure, or force applied to the skin) on their steering input (Knight, 1987). Since range of motion of the hand controller was rather small, viz. 1.5 mm in each direction for translations and 4° in each direction for rotations, the resulting haptic feedback probably was not sufficient to facilitate an accurate distinction between all six degrees of freedom. This can be solved by enlargement of the amplitude of the hand controller (for each DOF). As a result, the size of the haptic information relative to the noise will increase so that it will become more helpful. Another option is a more extensive use of haptic feedback, for example by increasing the resistance of the control as soon as more than one DOF is controlled. By providing more haptic feedback it can be expected that it is easier to differentiate between the degrees of freedom. As noted above, cross-talk is mainly related to motor limitations of the human operator. Therefore, it is expected that cross-talk will reduce when extra haptic information facilitates the initiation and correction of these motor actions.

In the 2-DOF condition there only was found a difference between Pitch-Z, and the other combinations with Pitch as a relevant DOF. The correlation between these 2 DOFs can still be considered reasonable (r=0.46). Despite the visual feedback on Z, there remained a reasonably systematical variation of input on Z with tracking input on Pitch. Something similar was found in the 6-DOF condition (r for Pitch-Z=0.47). On the contrary, in both conditions the correlation between Z-Pitch was remarkably reduced by visual feedback. This makes sense because the error on Z was perceived worse than on Pitch. Visual feedback on irrelevant Z therefore will be less helpful in reducing cross-talk than feedback on (irrelevant) Pitch.

Conclusions

The results of the present experiment showed that in the 1-DOF condition, the largest tracking errors were found for Z (with regard to translations), and Pitch (with regard to rotations). It was concluded that this was related to the limited depth cues available in the perspective display. The improvement of visual information concerning this DOF, e.g., by enhancing the quality of depth cues, or the diminishing of z-axis compression, is recommended. Besides, tracking performance decreased when the input on task-irrelevant degrees of freedom was displayed. The information processing system apparently had to divide its limited capacity over a growing number of degrees of freedom and therefore could allocate less attention to each individual DOF. For Z, the increase in the number of irrelevant degrees of freedom that had to be controlled (i.e., about which visual feedback was provided) resulted in a relatively large decrease of performance compared to the other DOFs. With regard to X, this effect was the other way around (both when X was relevant or irrelevant). Supposedly, the subjects needed relatively much attention for Z, and little attention for X as a consequence of the way these two DOFs were displayed (i.e., the limited depth cues available, and the compression of the y-, and z-axis in the display). Furthermore, a systematical relation (cross-talk) appeared between the input on a relevant DOF and the input on an irrelevant DOF (cross-talk). Visual feedback concerning the input on the irrelevant DOFs did result in some reduction of cross-talk although it was far from being eliminated. In fact, half the combinations of two degrees of freedom, were indifferent to changes in the amount of visual feedback or an increase in the number of irrelevant degrees of freedom that could be controlled. The latter point was actually true for all combinations. On the basis of these results it is concluded that cross-talk is mainly caused by limitations of the human motor system, and only to a minor extent related to information processing limitations. As a possibility to limit cross-talk between DOFs, it was suggested to improve the available haptic feedback. By an enlargement of the amplitude of the hand controller or increasing the resistance in the device when multiple DOFs are controlled simultaneously, the input on the different degrees of freedom can be better distinguished.

In brief: selective control of DOFs in a 3D manual controller is determined by the quality of the relevant visual information in combination with the amount of feedback on irrelevant DOFs. Systematic cross-talk among DOFs is primarily determined by motor constraints.

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Soesterberg, 4 July 1997

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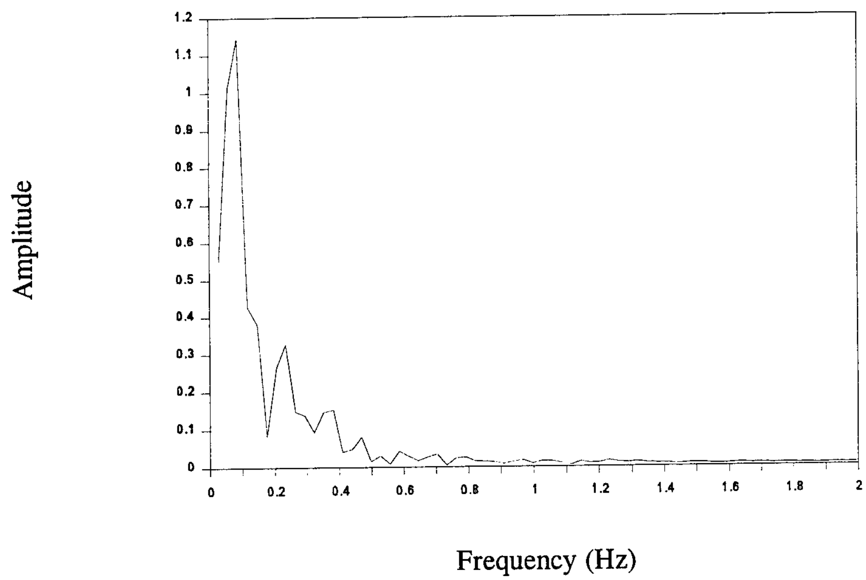
APPENDIX A Spectral analysis of the disturbance signal



Spectral analysis of the used disturbance. For each frequency component of the signal the amplitude is presented.

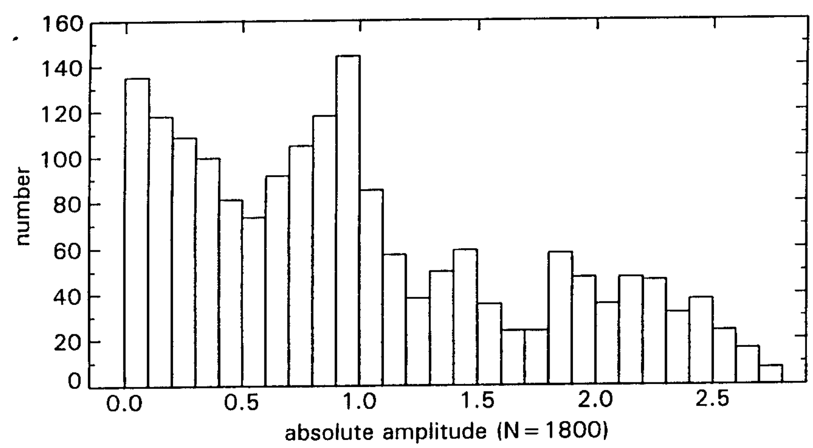


Fig. 6 Histogram with regard to the absolute amplitudes of the disturbance signal. These values were scaled to metres with a factor 0.25 for translations and to degrees with a factor 15 for the rotations. This resulted in a maximum amplitude of the disturbance signal for translations of 0.675 m (67.5 cm) and for rotations of 40.5°. De mean amplitude of the disturbance signal is 0 with a SD of 1.

APPENDIX B Technical specifications of the Space Mouse®

Measuring system	optical
Size (L×B×H)	165 mm, 112 mm, 40 mm
Weight	670 g
Cable length	2 m
Stiffness	3 N/mm
Translation range	±1,5 mm
Rotation range	±4°
Diameter knob	65 mm
Weight knob (without ball)	25 g
Connector	9 pins (female) D-Sub connector (IBM PC serial slot connector)
Power supply	RS232 handshake lines RTS and DTR (6,5 V, 9 mA)
RS232 interface	2D mode only 1200 BAUD transmission, Logitech M+ protocol 3D mode receiving and sending 9600 BAUD, 8 databits, 2 stopbits
Cyclus time	60 milliseconds (shortest interval between 2 consecutive data packets), 17 datapackets per second (fastest data transmission time).

Source: Space Mouse® User's Manual

APPENDIX C Technical specifications of the ESIG-2000 image generation system

Manufacturer	Evans & Sutherland, type ESIG-2000
Principle	computer generated images
Number of channels	1 (in the present experiment)
Resolution	1,0 M image elements per channel at 30 Hz
Image angle	programmable
Number of polygons	1500 or 2000 polygons/channel at 30 Hz dependent of the configuration, 1000 polygons/channel at 60 Hz
Colour	1024 basic colours apart from texture and shading effects
Hidden surface removal	based on Binary Separation Planes (BSP)
Shading	smooth, flat, Gouraud shading
Anti-aliasing	yes, not by transparent polygons
Moving objects	maximally 252 independent objects
Lag time	2½ update cycle + 1 refresh cycle. At 30 Hz update and 60 Hz refresh that is 100 ms.
Texturing	maximally 256 (128×128) texture maps (4,2 Mtexel). Dynamic texturing possible
Atmospheric conditions	day, night, twilight, thunder
Level of detail	automatic, overload management
Point light source	yes
Line of sight ranging/ laser ranging	yes
Collision detection	yes
Terrain interaction	yes, maximally 40 pixels
FLIR	yes
Animation	yes
Graphics overlay	mixed in the image by video-keying
Video-output	fully programmable
Modelling	EaSIEST modelling software on ESV/3 workstation

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10. TITLE AND SUBTITLE

Interference between 6 degrees of freedom in a 3D hand controller

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14. SUPPLEMENTARY NOTES

15. ABSTRACT (MAXIMUM 200 WORDS (1044 BYTES))

A six degree of freedom (DOF) hand controller is a device that can be used for the simultaneous control of multiple axes. These kinds of control tasks are common in areas such as teleoperation. Multi-axis control may be problematic as a consequence of interference i.e., the control of a certain DOF affected the simultaneous control of another. Irrespective whether the cause of this interference lies in the operator's motor system or in his information processing system, it can be detrimental to task performance. When input on one DOF always results in undesired input on another DOF, the nature of this interference is systematic (cross-talk). The magnitude of the interference is probably affected by the number of DOFs that has to be controlled simultaneously. This was investigated in an experiment in which a compensatory tracking task was performed. In this task one DOF of a cursor in a perspective display was disturbed (externally). Subjects had to compensate this disturbance using a 6-DOF hand controller. At the same time they had to minimize input on the other (irrelevant to tracking) DOFs. It was investigated whether there were differences between tracking performance between each separate degree of freedom (X, Y, Z, Roll, Pitch, or Yaw). Furthermore, the effect of additional (irrelevant) DOFs that had to be controlled simultaneously (0, 1, or 5), was examined. With regard to the irrelevant degrees of freedom, the steering error thus was completely caused by incorrect, accidental, steering inputs. Error on the relevant DOF was a sum of this incorrect steering input and the disturbance signal.
Both these errors (expressed in RMS scores) can be used to indicate the extent to which degrees of freedom interfered with each other. In this experiment a relative RMS score was calculated by dividing the RMS score with the mean RMS error score from the 1-DOF condition (no irrelevant DOFs) that was used as a baseline condition. This way, it was possible to gain insight in the performance increment or decrement as a function of the number of DOFs that had to be controlled. Through determination of the correlations between each combination of two degrees of freedom the extent to which systematic interference occurred was investigated.
The experimental results show that in the 1-DOF condition tracking error was largest on Z with regard to translations and on Pitch with regard to rotations. This can be related to the effectivity of the presentation of the z-axis (i.e., used depth cues and compression) in the used perspective display. Furthermore, performance on relevant as well as irrelevant DOFs decreased when the number of visible degrees of freedom that had to be controlled increased. These limitation are attributed to the limited information processing capacity of the human operator. In relation to the other DOFs, this performance decrement for Z was substantially larger whereas it was smaller for X Again this may be related to the effectivity of presentation of the different axes on the display. A clear training effect diminished the effect of interference in the second block of trials. For each DOF in each condition this effect was of the same magnitude.
Input on a relevant DOF and input on an irrelevant DOF were always significantly correlated. The amount of cross-talk between degrees of freedom did not change with the number of DOFs that had to be controlled. For half the combinations cross-talk even remained the same in the conditions without any visual information on the irrelevant DOFs. Therefore, it seems that cross-talk mainly results from motor limitations of the operator. Increasing the amount of haptic information in the hand controller, probably will help the operator to distinguish the degrees of freedom more easily. This may result in a reduction of cross-talk and better control.

16.	**DESCRIPTORS** Displays Feedback Manual Control Perceptual Motor Performance Tracking	**IDENTIFIERS** 3D Controls Cross-Talk Interference

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